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High-Brightness Milestone Report to DOE OFES, FY05 Q4

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FY05 Q4 Milestone: *Complete initial suite of experiments and comparison with theory on the accumulation of electrons in magnetic quadrupoles on HCX due to various sources, including gas ionization, emission from beam tubes, or emission from the end wall.*

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We have met this milestone by making measurements of electrons, as described in our FY05 Q3 Milestone Report, and simulating the same conditions with the WARP/POSINST code. This code has been developed over the last three years, by adding self-consistent electron and gas populations to the beam-dynamics particle-in-cell code, WARP, and combining it with the electron-cloud code from LBNL, POSINST. This code development effort has advanced to the point where almost all elements of a comprehensive "roadmap" are available. The WARP simulations shown here replicate experimental results, with agreement ranging from semi-quantitative agreement to close quantitative agreement.

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1. Introduction

Electron clouds and gas pressure rise limit the performance of many major accelerator rings, and may constrain the architectures of linacs being developed as drivers for near-term high-energy-density physics (HEDP) experiments and, in the longer-term, for heavy-ion-inertial fusion (HIF). For the last three years, we have had a multi-laboratory effort to understand the underlying physics through the coordinated application of experiment, theory, and simulation [1-13]. Our work applies a multiplicity of diagnostics and thoroughly tested simulation codes based on fundamental physics. This field is a hybrid of plasma physics and accelerator physics. This work is well regarded in the accelerator and fusion communities, as evidenced by the eight invited papers listed in the references. Electrons can arise from three sources: ionization of gas, beam-tube emission when impacted by ions, electrons or photons, and end-wall emission (as will be discussed). End-wall emission is not a problem, because electrostatic suppression can eliminate it; however it has proven to be a very useful tool by which to inject electrons for experimental and computational study. Here we report on our comparisons of simulations with experimental measurements. The diagnostics, and sample results, were discussed in our FY05 Q3 Milestone report.

We study electron cloud effects in the High-Current Experiment (HCX), shown in Fig. 1. A suppressor ring electrode, surrounding the beam after it exits the last quadrupole magnet, can be biased to –10 kV to prevent ion-induced electron emission off an end wall (a slit plate) from reaching the magnets, or can be left unbiased to allow electrons to be emitted from the end wall and to flow into the magnets. In order to calibrate diagnostics and simulations, we measured gas desorption and electron emission from 1 MeV K^+ ions

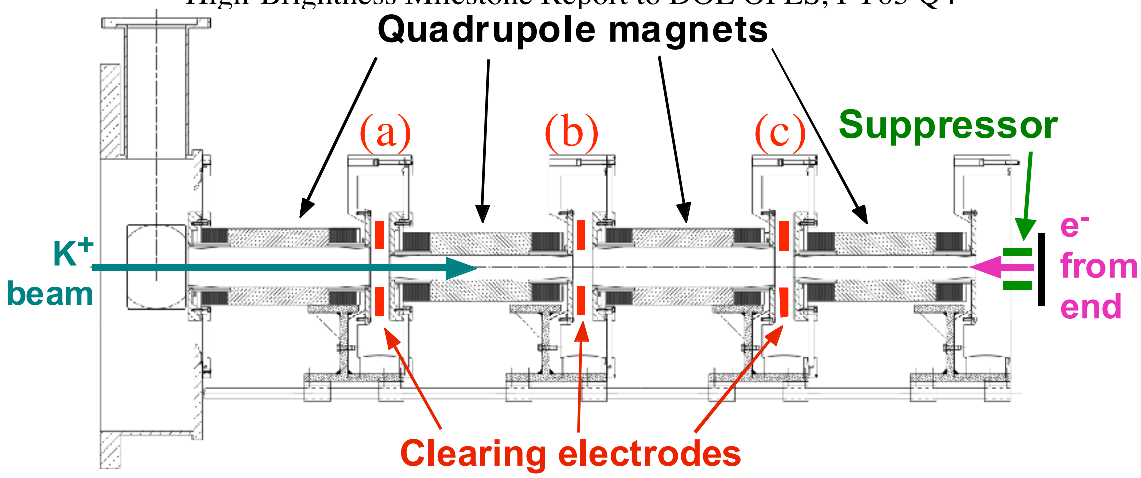

Fig. 1. Magnetic quadrupole region of HCX, from the D2 diagnostic region on the left to the D-End diagnostic region beginning on the right. The lattice half period length is 0.52 m. Clearing electrodes a, b, and c are shown in the drift regions between each pair of quadrupoles. A suppressor electrode prevents beam-induced electron emission, from structures hit by beam in D-End, from reaching the quadrupole magnets. Vacuum pumps are located in each of the diagnostic tanks a-c, as well as at both ends of the region shown. Gas can be fed at tank b.

at angles near grazing incidence [3]. This work lead to basic physics studies of gas desorption scaling with ion energy, showing that the desorption scales with the electronic component of ion slowing in matter $(dE/dx)^n$ where $1 \leq n \leq 2$ [14]. A similar study of electron emission from ion impact showed that the emission scales linearly with the electronic component of dE/dx [15]. Related previous work includes studies of high fill factor transport in electrostatic quadrupoles [16].

The simulation capability is based on a merge of the three-dimensional parallel Particle-In-Cell accelerator code WARP [17] and the electron cloud code POSINST [18], with additional functionalities. POSINST has been developed for E-cloud studies in high-energy accelerators or storage rings. WARP is a multidimensional intense beam simulation program being developed and used by the Heavy Ion Fusion (HIF) Virtual National Laboratory, whose near-term goal is to develop heavy-ion accelerators capable of heating matter for the study of high-energy density physics, with the ultimate application to igniting inertial-fusion targets for electric-power production [19]. The two codes possess complementary capabilities that are both necessary but not sufficient for self-consistent simulations of HIF beams and their interactions with electron cloud and desorbed gas. Newly developed functionalities include a novel particle mover bridging the time scales between electron and ion motion [11], a module to generate neutrals desorbed by beam ion impacts at the wall, and a module to track impact ionization of the gas by beam ions or electrons.

As already noted in the FY04Q4 milestone report, we have established a list of different functional modules, and their inter-relationships, that are ultimately needed to reach self-consistency for the modeling of HIF beams with e-cloud and gas, and have summarized it in a block diagram (see Fig. 1 in that report). We imagine this as a “roadmap” that we need to follow in order to develop our simulation tools. An updated version of the roadmap which reflects the current status of development of the simulation capability is given here in Fig. 2.

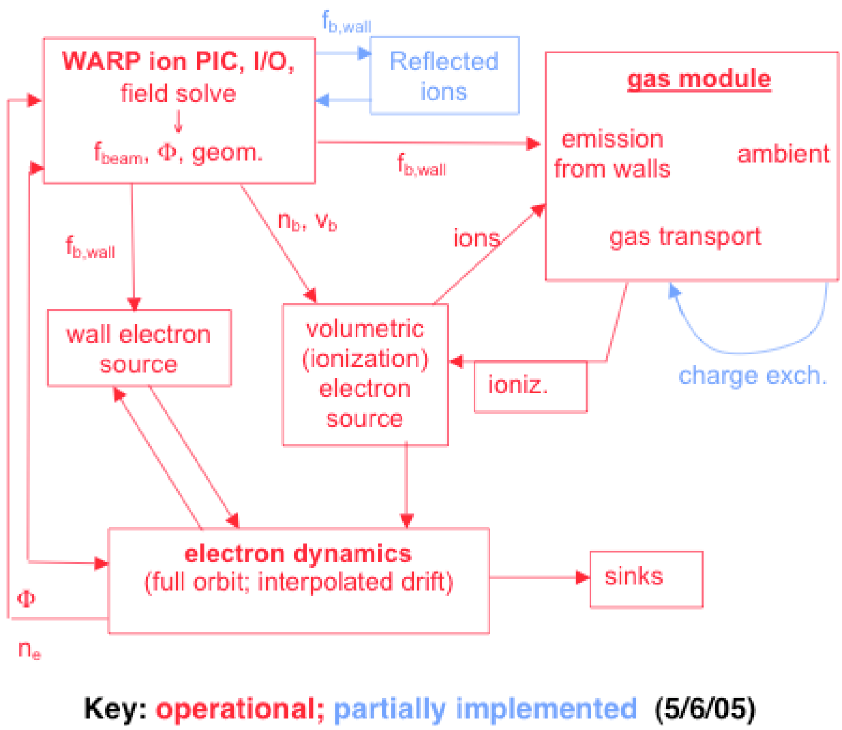

Figure 2. "Roadmap" describing the different functional modules, and their inter-relationships, that are ultimately needed to reach self-consistency for the modeling of HIF beams with e-cloud and gas. At the time of this writing, most modules are operational, excepting the "reflected ions" and the "charge exchange" modules that are still being developed.

2. Evaluation of existing electron sources

Electrons can arise from three sources: ionization of gas, beam-tube emission when impacted by ions, electrons or photons, and end-wall emission. End-wall emission is not a problem, because electrostatic suppression can eliminate it. When we bias the suppressor electrode to –10 kV, we eliminate electrons from the end wall, but we still have a small current from other sources to the clearing electrodes between magnets.

We can also prevent electrons off the end-wall from reaching clearing electrodes A or B by biasing Clearing-C to ≥4 kV, as shown in Fig. 3. We have made other measurements and done simulations to understand the source of the remaining electrons to clearing electrodes A and B.

Experimentally, we have varied the background pressure by injecting carbon dioxide gas, and measured the currents to the clearing electrodes, Fig. 4. We found that the clearing electrode current increased with gas pressure, confirming that ionization of gas is a source of electrons; however extrapolation to zero gas pressure shows that most of the clearing current at the base pressure of 3E-7 torr is from another source.

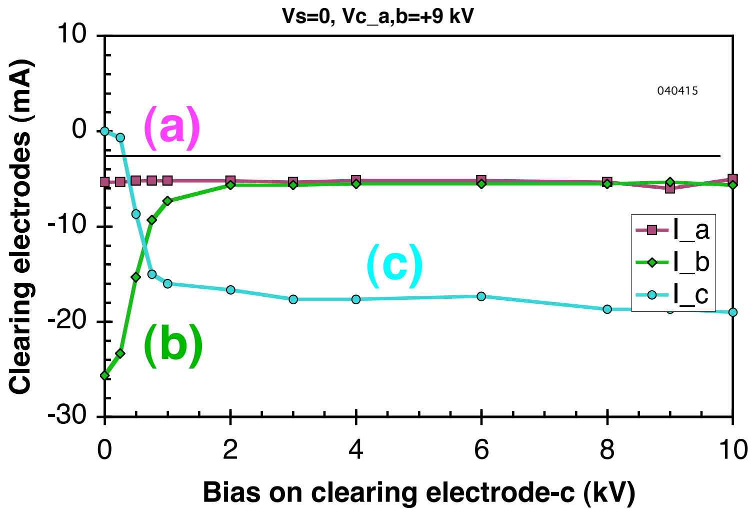

Fig. 3. The currents to Clearing electrodes A, B, and C are plotted versus the bias voltage on clearing electrode-C, with the suppressor bias off. When C is biased to voltages greater than +4 kV, it collects all the electrons from the end wall, preventing them from reaching electrodes A or B. However, these electrodes still draw a current of ~3 mA.

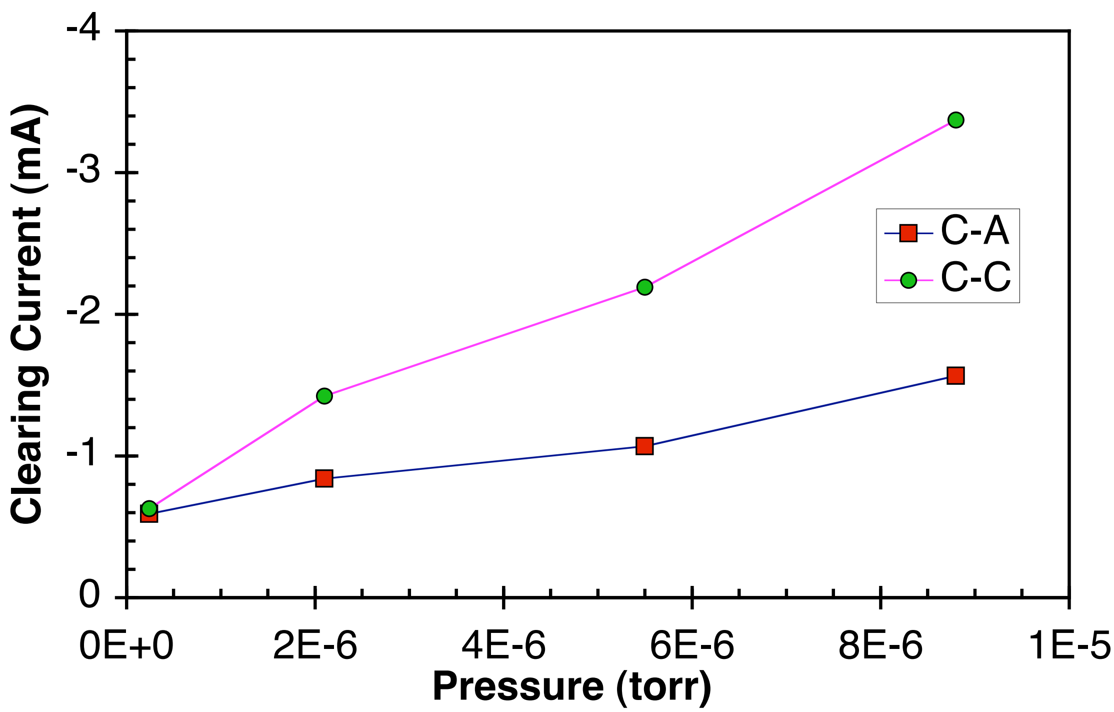

Fig. 4. The current to clearing electrodes A and C is shown as a function of the background gas pressure. Extrapolation to zero pressure shows that most of the clearing current at base pressure (3E-7 torr) is not from ionization of gas. Electrode-A is between a pump and the gas bleed at Gap-B, therefore it is at lower pressure than C, which may account for the smaller current at A at higher pressure.

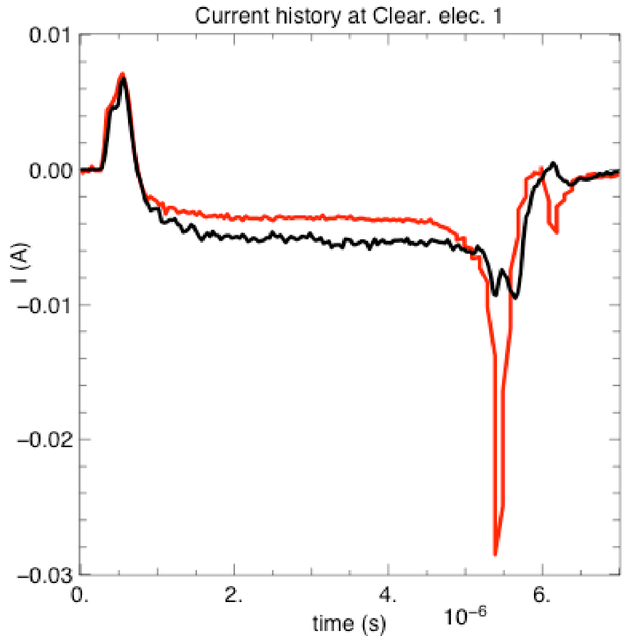

Fig. 5. Simulation of clearing electrode-A (black) at 9E-6 torr, compared with the measured current (red) at the base pressure of 3E-7 torr.

Simulations reach a similar conclusion, Fig. 5. By increasing the pressure in the simulation to 9E-6 torr, 30 times the base pressure of 3E-7 torr in the experiment, and using an ionization cross section of 2E-15 cm^2, the simulated current to clearing electrode-A approximated that measured, rather than being much smaller as seen in Fig. 6. Interestingly, the time dependence of the simulated current is close to that measured.

Thus the experiment and simulation agree that most of the electron current to the clearing electrodes is not due to ionization of gas within the magnets. The suppressor has been shown to effectively block emission from the end wall, furthermore clearing electrode-C was shown in Fig. 2 to remove all axially drifting electrons before they reach clearing electrodes A or B. The remaining identified source is beam tube emission: this could arise from ion beam halo scrape-off, or from ionization and charge exchange of the beam on gas upstream from the magnets that results in 1 MeV K^0 or K^{++} that strike the beam tube. These hypotheses are being pursued.

3. Studies with electrons from end-wall emission

Early observations with unsuppressed end-wall emission, and one clearing electrode biased for each shot, showed a delay in electrons reaching clearing electrodes that increased with the distance from the end wall, Fig. 6. Simulations produced remarkable agreement with the time of arrival. This indicates that the beam potential is being accurately simulated because the electron velocity through a quadrupole magnet is the sum of E x B, grad-B, and curvature drift velocities: the E x B velocity scales linearly with the electric field which is proportional to the beam potential, grad-B and curvature drift velocities are proportional to the electron energy perpendicular and parallel respectively to the magnetic field – these energies will also vary linearly with the beam potential, because an electron created anywhere, except at the peak beam potential (i.e.,

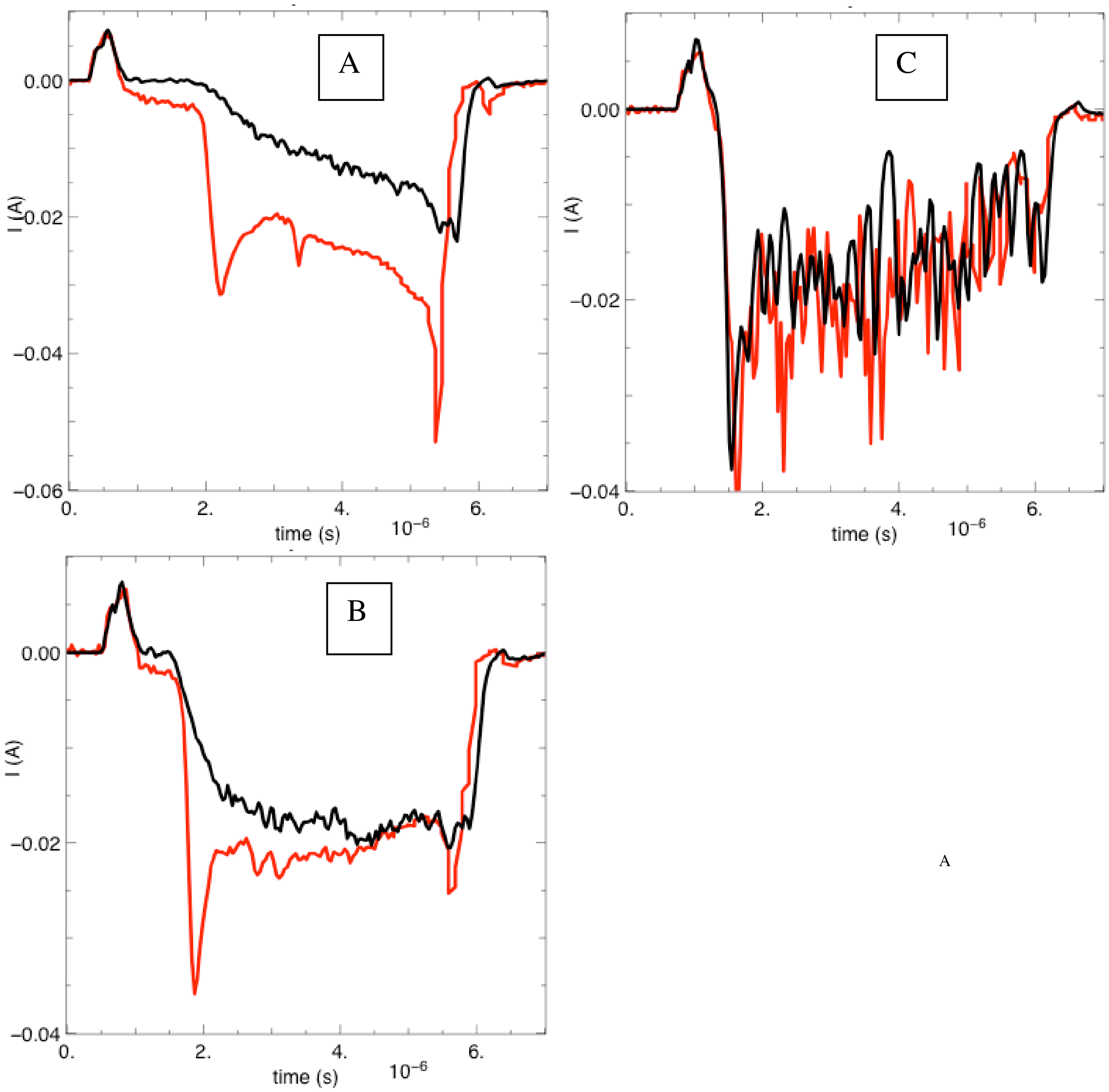

Fig. 6. One clearing electrode is biased for each shot, with the suppressor off to allow end-wall emission to reach the quadrupole magnets. Measurements (red) and simulations (black) agree in the arrival times of electrons: first reaching electrode C, subsequently reaching electrodes B and A respectively.

near the beam axis), will be accelerated to an energy of some fraction of the beam potential.

We also note that the magnitude of the simulated current agrees very well for electrode C, but less well for electrodes A and B, for reasons discussed in Section 2. The agreement for clearing electrode C is particularly intriguing as both the experiment and the simulation show significant oscillations in the current, and they agree in the frequency and magnitude of the oscillations as well as the overall signal level.

These oscillations, as well as another plot from these simulations in the RZ plane, shown in Fig. 7, indicate an apparent instability in the fourth quadrupole magnet. We have initiated further study of this phenomenon through simulation and diagnostics,

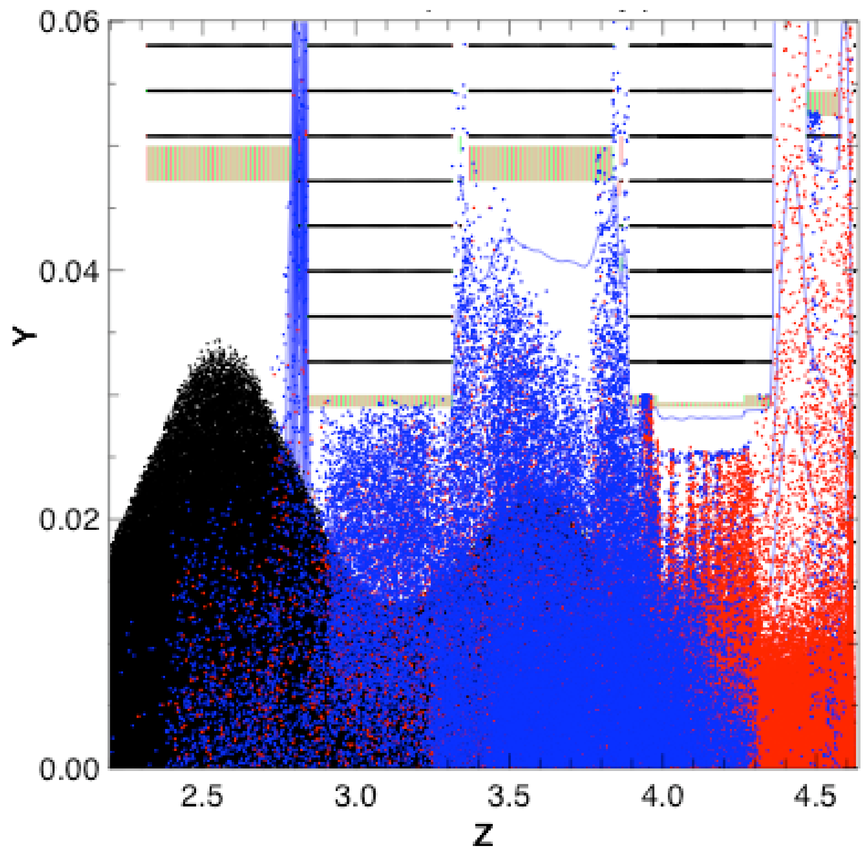

Fig. 7. We show WARP simulation results for an emitting end wall. We show the ion beam (black), primary electrons (red) and secondary electrons (blue). The last color to be plotted obscures earlier colors. An oscillation is seen in magnet 4, from 3.9 to 4.3 m.

which will be reported by Molvik at the APS Division of Plasma Physics Conference in Denver, October 24-28, 2005.

Electron cloud effects generally occur gradually, over many passes of a beam through an accelerator ring. However, we have demonstrated in both experiment and simulation that, when electron densities approach the beam density, electrons can significantly degrade beam properties in the short distance of 2 lattice periods (four quadrupole magnets) in a linac.

An example of the effect of switching the suppressor on and off is shown in Fig. 8. With the suppressor on to suppress electron emission from the end wall, we minimize electrons, yet the experiment still shows small kinks at the ends of the XX' phase space plots with a slight "Z" behavior. With the suppressor off to allow electron emission from the end wall to enter the quadrupole magnets, we see large kinks with a strong "Z" distortion of phase space. Simulations using a semi-Gaussian beam with the suppressor on, resulting in no electrons in the beam, show a well-behaved ion beam with no Z-like kinks in the phase-space distribution. Simulations with the suppressor off allow electron densities to approach the beam density; this produces significant effects on the beam, qualitatively reproducing the dominant Z-phase space. Further details are available in Ref. [11].

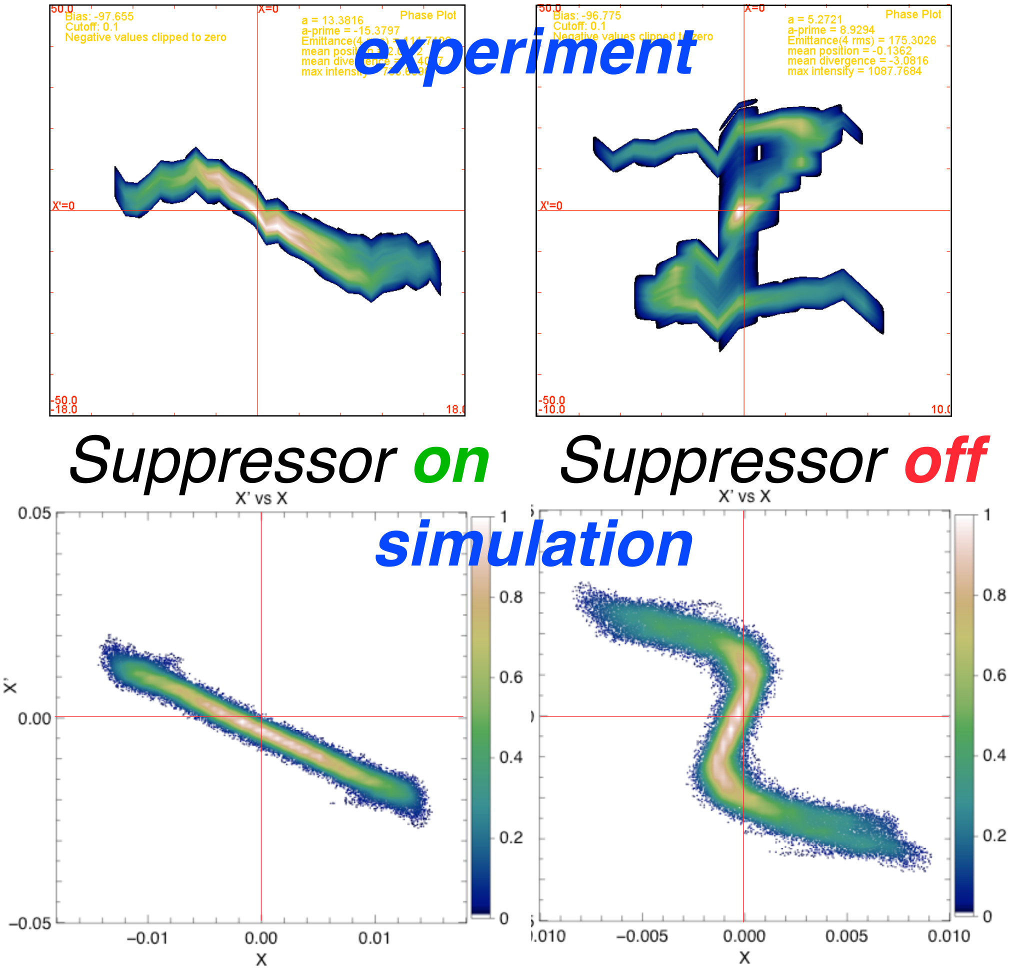

Fig. 8. The experimental X’ X phase space is measured with an optical slit scanner developed by F. Bieniosek. The WARP simulation demonstrates semi-quantitative agreement with the experiment using semi-Gaussian beams.

Initial simulations without electrons used a semi-gaussian distribution and showed little of the “hooking” or incipient “Z-ing” seen in the experiment even with the suppressor on, as shown in Fig. 8. It was tempting to ascribe these effects to residual electrons, and perhaps part of the effect is due to electrons; however, using a tool developed in a student project, we recently “synthesized” [20] a beam distribution from optical diagnostics [21,22] at D2 (immediately preceding the quadrupole magnets), which, when used to initialize Warp PIC runs without electron effects, does recover much of the phase space distortion observed in the experiment, Fig. 9. This is being explored further, by checking with other magnet tune settings, and via a systematic set of simulations with a (high) phase advance, which mimics the experimental conditions.

These results emphasize the importance of developing self-consistent codes, and carefully benchmarking them against experiments under a variety of conditions, in order to gain confidence in the predictive capability of a code and to be confident that agreement with experiment is not merely fortuitous.

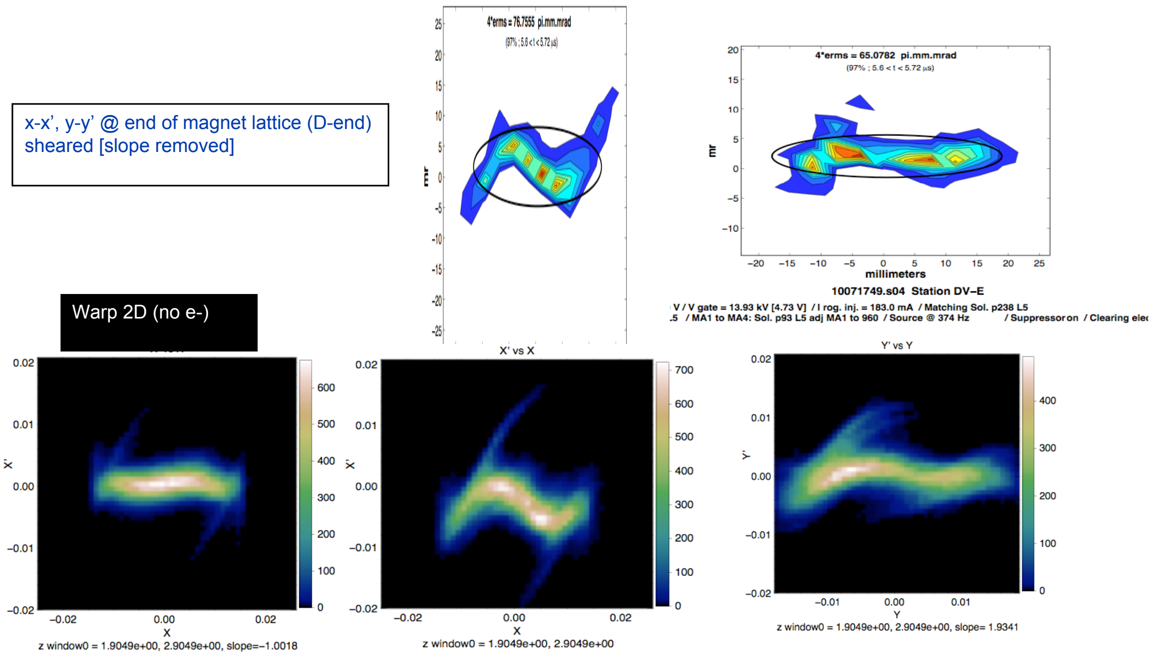

Fig. 9. Simulation initialized with reconstructed 4D phase space from upstream optical diagnostic captures the observed distribution distortions downstream. The top center and right show the experimental X-X' and Y- Y' distributions. The corresponding WARP results are below, using the reconstructed phase space without electrons. The lower left shows the X-X' view of the WARP simulation with semi-Gaussian beam distribution.

We have also applied the reconstructed beam to computing beam profiles in X-Y space. Scintillator measurements of the beam showed a somewhat-asymmetric approximately-diamond-shaped beam in Gap B (between magnets 2 and 3 in Fig. 1). Simulations with semi-Gaussian beams failed to reproduce these details in the beam shape. However, using the reconstructed beam profiles, the similarity of the simulated and measured beam shapes is striking, Fig. 10.

This agreement on shape is of more than academic interest. First, it provides reason to hope that future reconstructions will enable beam head scraping and halo scraping simulations to agree with experiment. Simulations should then replicate the measured clearing electrode currents to electrodes-A and B. Secondly, we are measuring the beam potential as a function of time with a retarding potential analyzer (RPA). This summer, a student project succeeded in computing the beam potential contours for the beam profile measured with the scintillator.

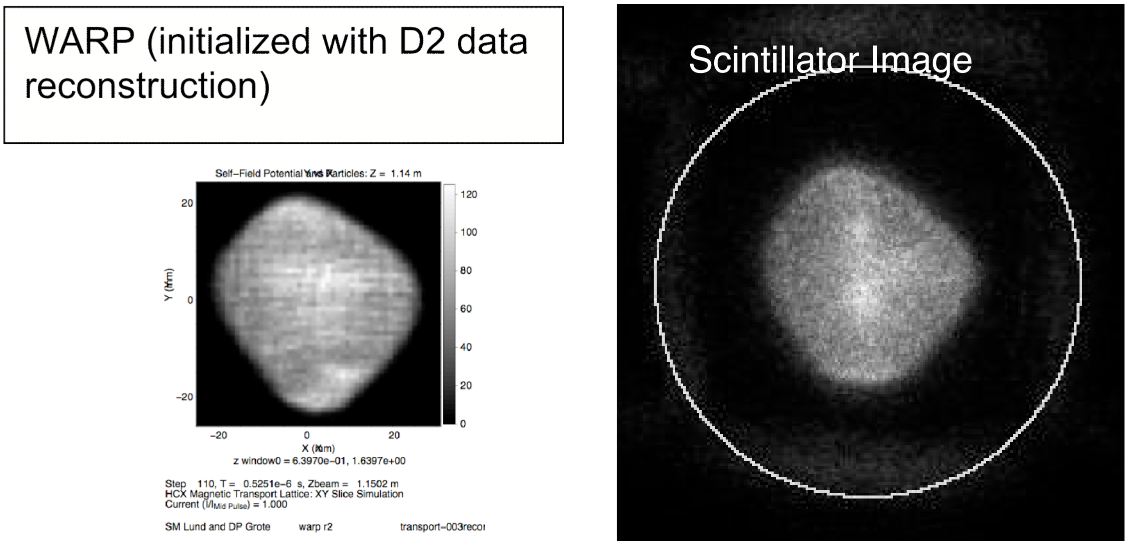

Fig. 10. Simulated (with reconstructed beam distribution) and measured beam profiles at gap-B.

Conclusions

This work successfully applied a multiplicity of diagnostics and thoroughly tested simulation codes based on fundamental physics, the electron cloud field is a hybrid of plasma physics and accelerator physics.

The WARP/POSINST simulations shown here replicate experimental results with agreement ranging from semi-quantitative agreement to close quantitative agreement.

This work is well regarded in the accelerator and fusion communities, as evidenced by the eight invited papers listed in the references.

The accelerator community is expressing interest in using these new tools, especially the simulation tools.

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